Selected topics of the deep exclusive reactions program of CLAS12: highlights and perspectives

Pierre Chatagnon,

for the CLAS collaboration

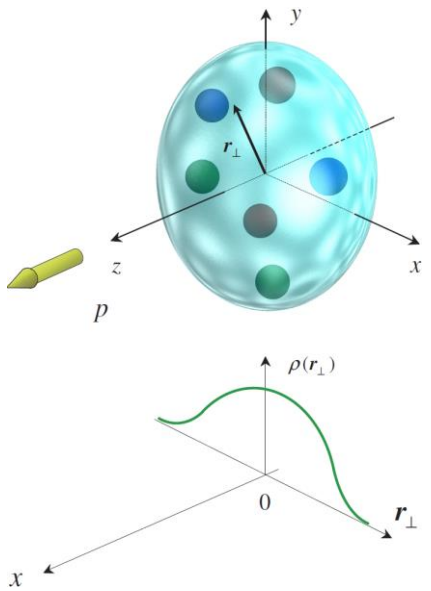
2023 JLUO annual meeting

27th of June 2023

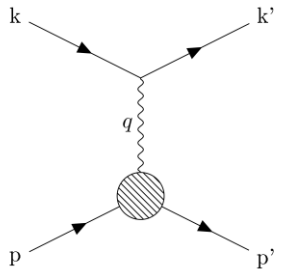
Jefferson Lab clas

The Generalized Parton Distributions…

Form Factors



Accessed via elastic scattering

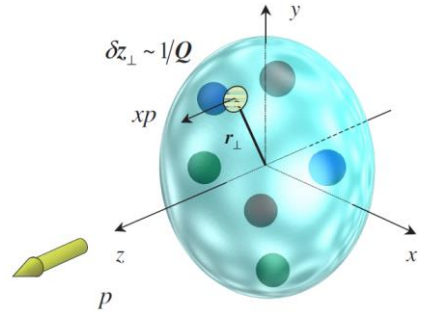


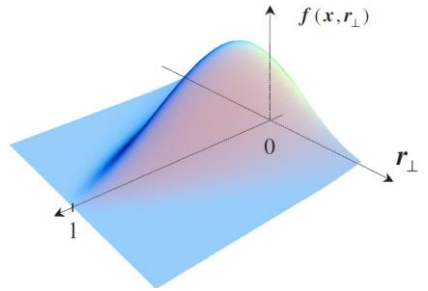
Position in the transverse plane

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

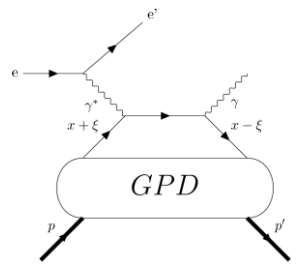
GPDs

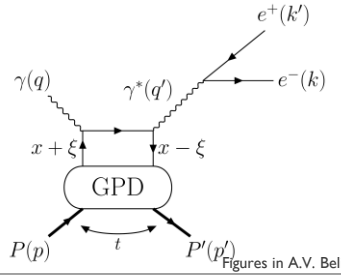




… and their correlations

Accessed via exclusive reactions

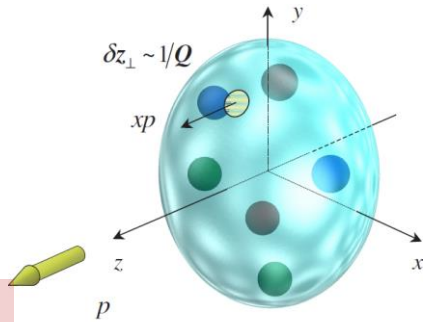


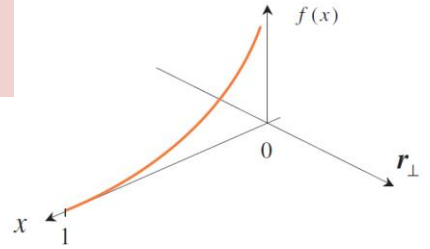


Momentum in the longitudinal direction

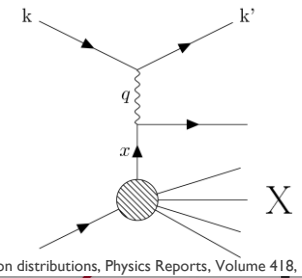
$$H^q(x,0,0) = \begin{cases} q(x), & x > 0 \\ -\bar{q}(-x), & x < 0 \end{cases}$$

PDFs





Accessed via Deep Inelastic Scattering

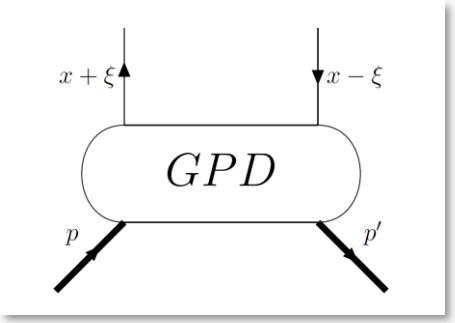


Figures in A.V. Belitsky, A.V. Radyushkin, Unraveling hadron structure with generalized parton distributions, Physics Reports, Volume 418, Issues 1–6 2005

…and their properties

Some properties of GPDs

- 8 GPDs for spin ½ particles at leading twist:
  - 4 chiral-even GPDs: H, E, $\tilde{H}$, $\tilde{E}$
  - 4 chiral-odd GPDs: H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$
- They depends on three variables:
  - x, the average momentum of the struck quark,
  - ξ, the transferred longitudinal momentum fraction,
  - the Mandelstam variable t.



Compton Form Factors

- GPDs are usually not accessible directly, but through complex quantities, the Compton Form Factors:

$$\mathcal{H} = \int_{-1}^{1} dx H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$

What can we learn from the GPDs ?

- Tomography of the nucleon: the Fourier transform of the GPDs can be interpreted as a probability density:

$$H^q(x,b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ib_\perp \Delta_\perp} H^q(x,0,-\Delta_\perp^2)$$

- Understanding the spin composition of the nucleon (aka the "spin puzzle") using the Ji's sum rule:

$$\frac{1}{2} = J_Q + J_G \longrightarrow J_Q = \sum_q \frac{1}{2}\int_{-1}^{1} dx\, x(H^q(x,\xi,0) + E^q(x,\xi,0)) = \sum_q \frac{1}{2}(A^q(t) + B^q(t))$$

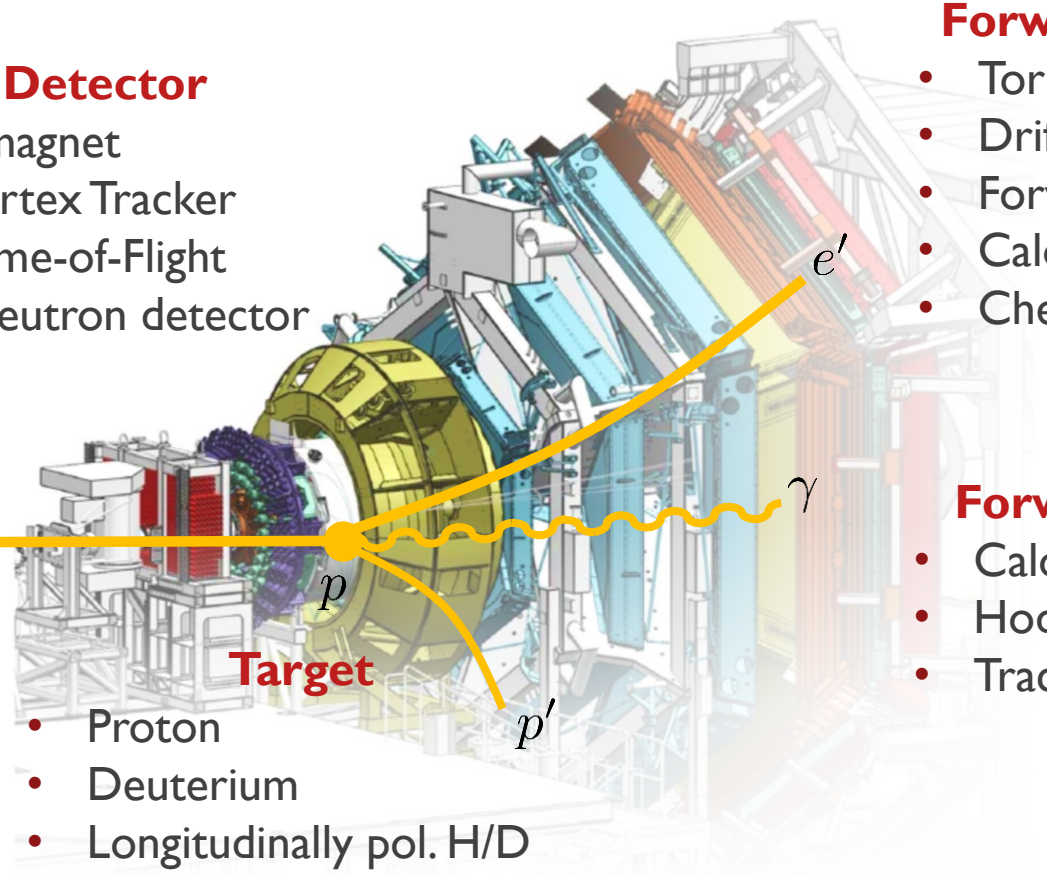
- Accessing Gravitational Form Factors by mimicking a spin-2 interaction:

$$\int_{-1}^{1} dx\, xH^q(x,\xi,t) = A^q(t) + \xi^2 D^q(t) \qquad \int_{-1}^{1} dx\, xE^q(x,\xi,t) = B^q(t) - \xi^2 D^q(t)$$

The CLAS12 detector

Central Detector
- Solenoid magnet
- Central Vertex Tracker
- Central Time-of-Flight
- Central Neutron detector

Forward Detector
- Torus magnet
- Drift Chambers
- Forward Time-of-Flight
- Calorimeters
- Cherenkov counters



Beam
- 85% longitudinally polarized electrons
- Max. luminosity: 10^{35} $s^{-1}cm^{-2}$
- Energy: 6.5 / 7.5 / ~10.6 GeV

Target
- Proton
- Deuterium
- Longitudinally pol. H/D

Forward Tagger
- Calorimeter
- Hodoscope
- Tracker

Deep exclusive reactions program of CLAS12

Reaction	Observable	Experimental configuration	Lead analyzer (Affiliation)	Status
DVCS on proton	BSA	RG-A (Proton target)	G.Christiaens/M. Defurne (CEA Saclay)	Published (PRL)
DVCS on proton	Cross-section	RG-A	S. Lee (ANL)	Internal review
DVCS on bound neutron	BSA	RG-B (Deuterium target)	A. Hobart/S. Niccolai (IJCLab Orsay)	Internal review
DVCS on bound proton	BSA	RG-B	A. Hobart/S. Niccolai (IJCLab Orsay)	Internal review
Coherent DVCS on deuterium	BSA	RG-B	A. Biselli (Fairfield U.)	Ongoing
DVCS on proton	BSA	RG-K (Proton target, 6.5 and 7.5 GeV beam)	J.A. Tan (Kyungpook National U.)	Ongoing
DVCS on proton	BSA/TSA/DSA	RG-C (Longitudinally polarized target)	S. Polcher (CEA Saclay)	Ongoing
DVCS on neutron	BSA/TSA/DSA	RG-C	N. Pilleux (IJCLab Orsay)	Ongoing
Tagged DVCS on neutron	BSA	RG-F (BONuS12)	M. Ouillon (IJCLab) / M.Hattawy (ODU)	Ongoing
TCS on proton	BSA/AFB	RG-A	P. Chatagnon (JLab)	Published (PRL)
TCS on proton	BSA/TSA/DSA	RG-C	K. Gates (Glasgow)	Ongoing
DVMP π^0	BSA	RG-A	A. Kim (UConn)	To be submitted to PLB
DVMP π^0	Cross-section	RG-A	R. Johnston (MIT)	Ongoing
DVMP π^+	BSA	RG-A	S. Diehl (Giessen/UConn)	Published (PLB)
DVMP ρ	BSA	RG-A	N. Trotta (UConn)	Ongoing
DVMP ϕ	Cross-section	RG-A	P. Moran (MIT)	Ongoing
DVMP ϕ	BSA	RG-B	N. Ram (CEA Saclay)	Ongoing
DVMP π^- on Δ^{++}	BSA	RG-A	S. Diehl (Giessen/UConn)	Just accepted in PRL
J/ψ photoproduction on proton	Cross-section	RG-A	P. Chatagnon (JLab)	Ongoing
J/ψ photoproduction on neutron	Cross-section	RG-A	R. Tyson (Glasgow)	Ongoing
Tagged J/ψ photoproduction on proton	Cross-section	RG-A	M. Tenorio Pita (ODU)	Ongoing

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Coherent DVCS on deuterium	BSA	RG-B	[illegible] (Fairfield U.)	Ongoing
DVCS on proton	BSA	RG-K (Proton target, 6.5 and 7.5 GeV beam)	J.A. Tan (Kyungpook National U.)	Ongoing
DVCS on proton	[illegible]	[illegible]	[illegible]	[illegible]
DVCS on neutron	BSA/TSA	RG-C	N. Pilleux (IJCLab Orsay)	Ongoing
Tagged DVCS on neutron	BSA	RG-F (BONuS12)	M. Ouillon (IJCLab) / M.Hattawy (ODU)	Ongoing
TCS on proton	[illegible]	[illegible]	[illegible]	[illegible] (PRL)
TCS on proton	BSA/TSA	RG-G	K. Gates (Glasgow)	Ongoing
DVMP π^0	BSA	RG-A	A. Kim (UConn)	To be submitted to PLB
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DVMP ϕ	BSA	RG-B	N. Ram (CEA Saclay)	Ongoing
DVMP π^- on Δ^{++}	BSA	RG-A	S. Diehl (Giessen/UConn)	Just accepted in PRL
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J/ψ photoproduction on neutron	Cross-section	RG-A	R. Tyson (Glasgow)	Ongoing
Tagged J/ψ photoproduction on proton	Cross-section	RG-A	M. Tenorio Pita (ODU)	Ongoing

Disclaimer:

1) I did my best to mention all analysis and involved analyzers. I might have missed some.
2) Each of these analysis is worth a 20-minutes presentation (at least). Apologies for only flashing some of the results.

Outline

I Deeply Virtual Compton Scattering measurements

II Timelike Compton Scattering measurements

III Deeply Virtual Meson Production measurements

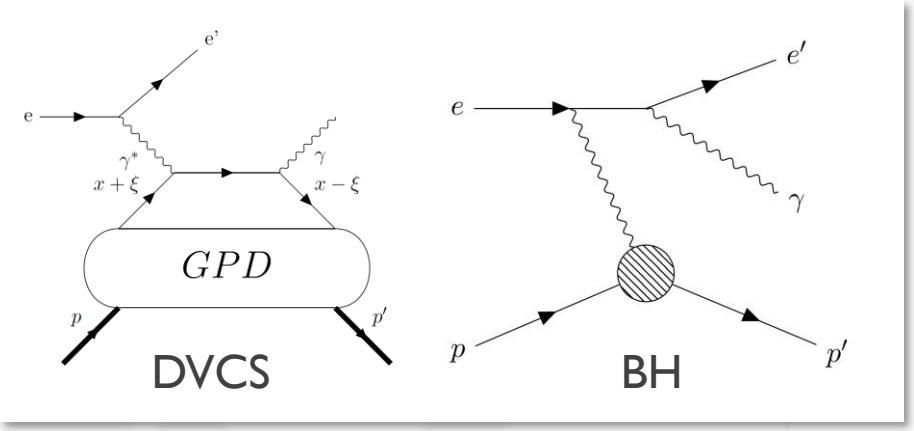
V Selected perspectives

First CLAS12 measurement of DVCS beam-spin asymmetries in the extended valence region

Lead analyzers: G.Christiaens/M.Defurne (CEA Saclay)

Deeply Virtual Compton Scattering: the golden process to access GPDs

- Reaction of interest: $ep \rightarrow e'p'\gamma$
- In the factorization regime $-t \ll Q^2$, GPD describe the soft structure of the proton

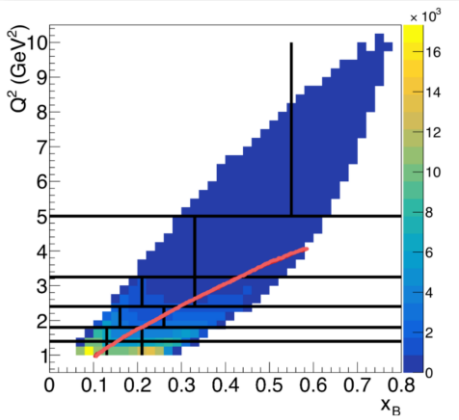


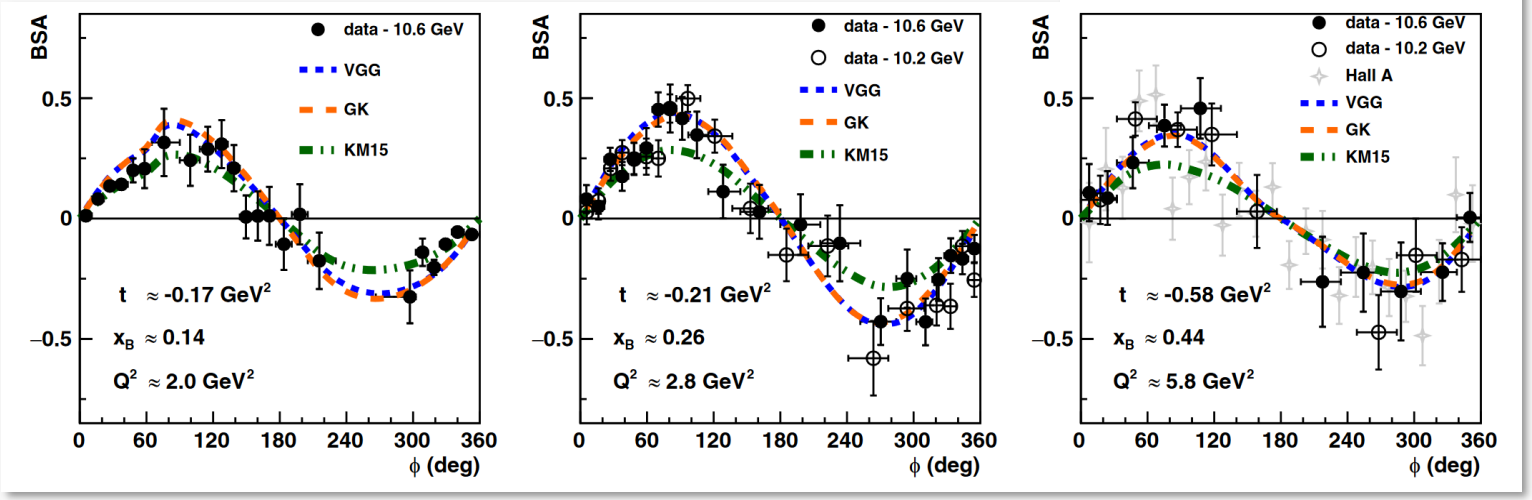
Published results

- Beam spin asymmetry extracted in wide phase space

$$A_{LU} \propto Im\left[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$$

- 1600 new data points
- Based on 25% of the total beam time allocated to CLAS12 DVCS experiment on unpolarized proton





Figures in First CLAS12 Measurement of Deeply Virtual Compton Scattering Beam-Spin Asymmetries in the Extended Valence Region, G. Christiaens *et al.* (CLAS Collaboration) Phys. Rev. Lett. 130, 211902

Published in PRL (2023)

Jefferson Lab clas

Measurement of pDVCS cross-section

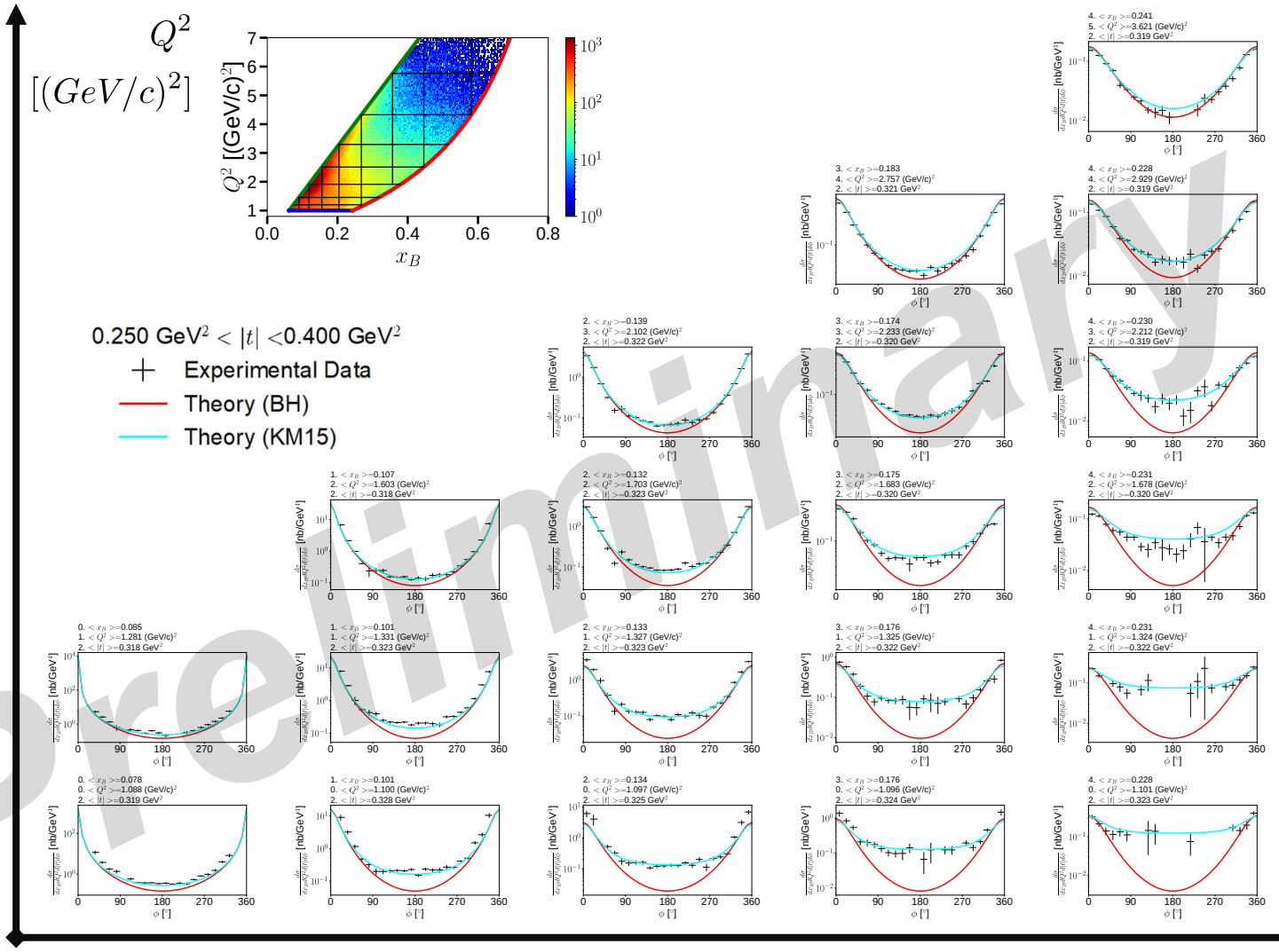
Lead analyzer: S. Lee (ANL)

Motivations

- Cross section sensitive to both Im($\mathcal{H}$) and Re($\mathcal{H}$)

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\phi} \propto (|\mathcal{T}^{\mathcal{BH}}|^2 + |\mathcal{T}^{\mathcal{DVCS}}|^2 + 2Re\mathcal{T}^{\mathcal{DVCS}}\mathcal{T}^{\dagger\mathcal{BH}})$$

- Crucial measurement to completely understand DVCS and GPDs
- Normalization under scrutiny by the collaboration



Internal review

Measurement of nDVCS beam spin asymmetry

Lead analyzers: A.Hobart/S.Niccolai (IJCLab Orsay)

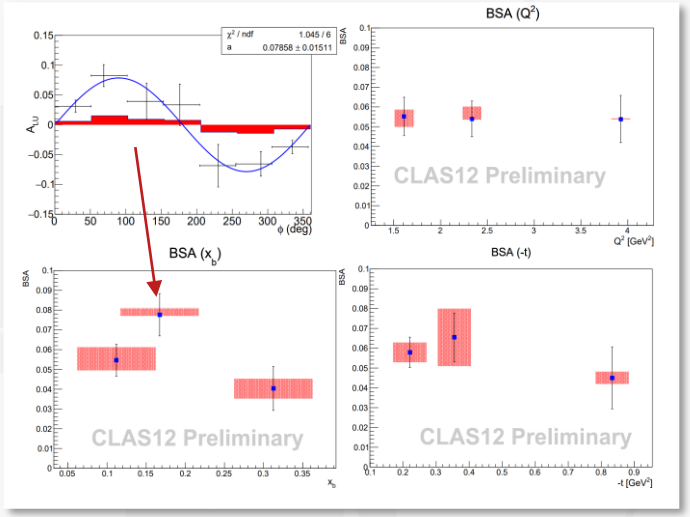
Preliminary BSA results

- nDVCS BSA is mostly sensitive to the GPD E…

$$A_{LU} \propto Im\left[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$$

- … which is a key ingredient to understand the spin composition of the nucleon

$$J_Q = \sum_q \frac{1}{2}\int_{-1}^{1} dx\; x(H^q(x,\xi,0) + E^q(x,\xi,0))$$



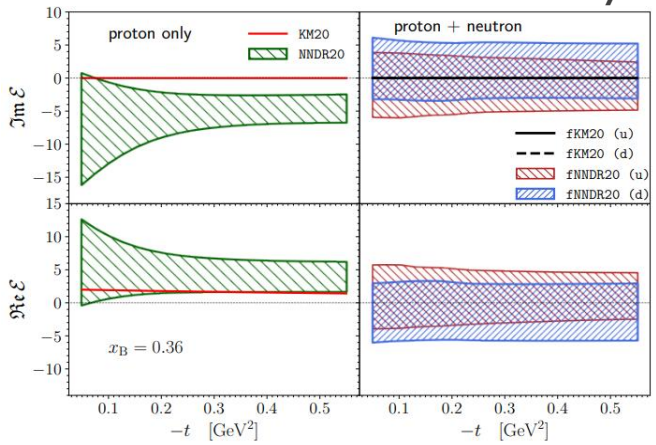
Impact on CFF extraction and flavor decomposition

- Measuring nDVCS and pDVCS allows for a flavor separation of the GPDs

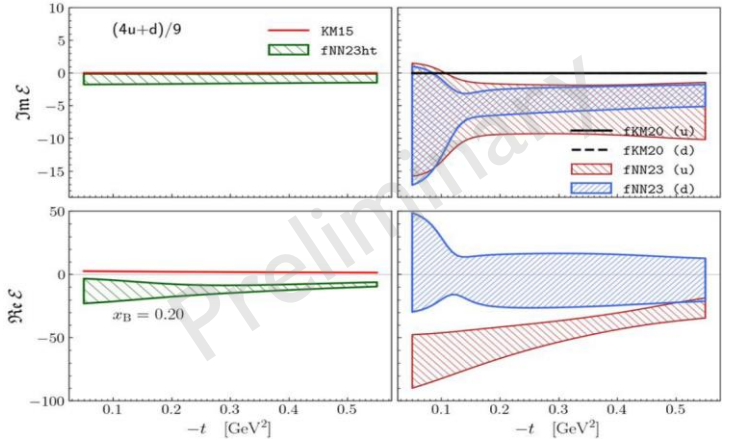
$$H_u = \frac{9}{15}\left[4H_p - H_n\right] \qquad H_d = \frac{9}{15}\left[4H_n - H_p\right]$$

- Impact of the new nDVCS data have been tested on a NN fit to the data

CLAS6 and Hall A data only



Including new nDVCS CLAS12 data



Credit: Marija Čuić and Krešimir Kumerički

Parallel measurement of bound proton DVCS

Internal review

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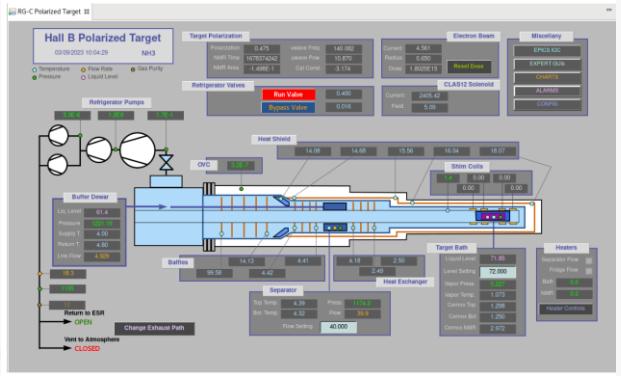
Proton and neutron DVCS BSA and TSA on a longitudinally polarized target

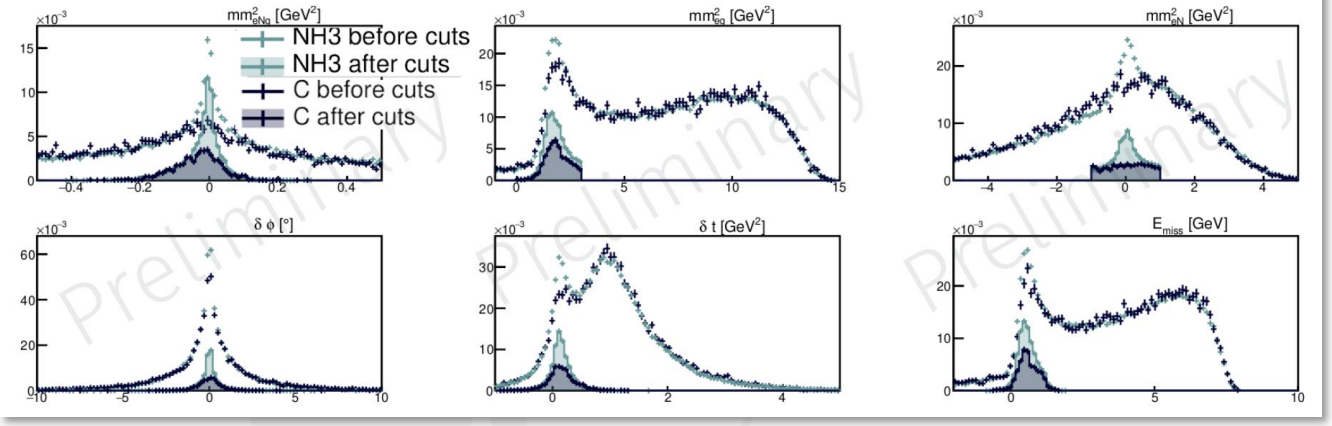
Lead analyzers: N. Pilleux (IJCLab) / S.Polcher (CEA Saclay)

Longitudinally polarized target for CLAS12 (RG-C)

- Target cell under 5T solenoid magnetic field, in a 1K cryostat.
- Samples are polarized using microwaves
- Target samples: NH_3, ND_3, C, CH_2, CD_2
- Data taken from June 2022 to March 2023

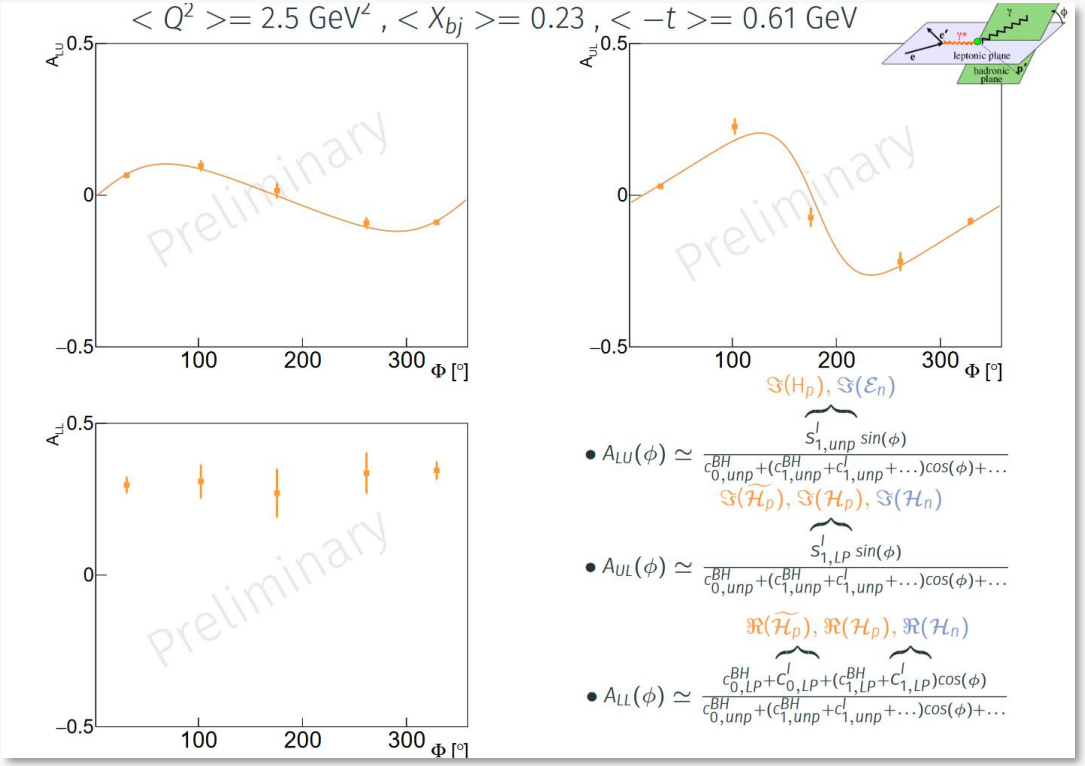


Background suppression method using carbon data



Preliminary results for pDVCS

- Based on only ~6% of the total dataset
- With incomplete calibration



Figures from N. Pilleux

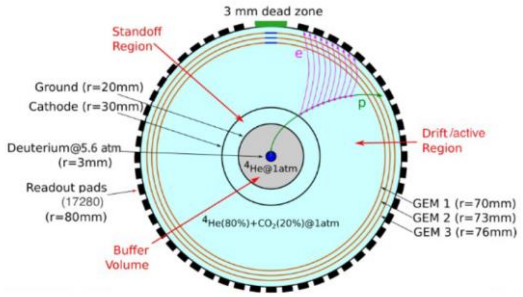
Ongoing analysis

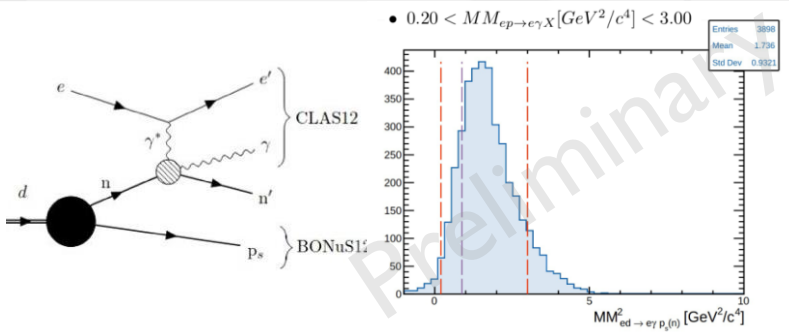
Other DVCS measurements: tagged nDVCS, DVCS on deuterium and more

Tagged neutron DVCS with Bonus12

Lead analyzers: M.Ouillon (IJCLab) / M. Hattaway (ODU)

- Use the BONuS12 TPC to detect spectator proton
- 2 topologies are explored (proton-tagged and fully tagged)





Proton-tagged analysis by M.Ouillon

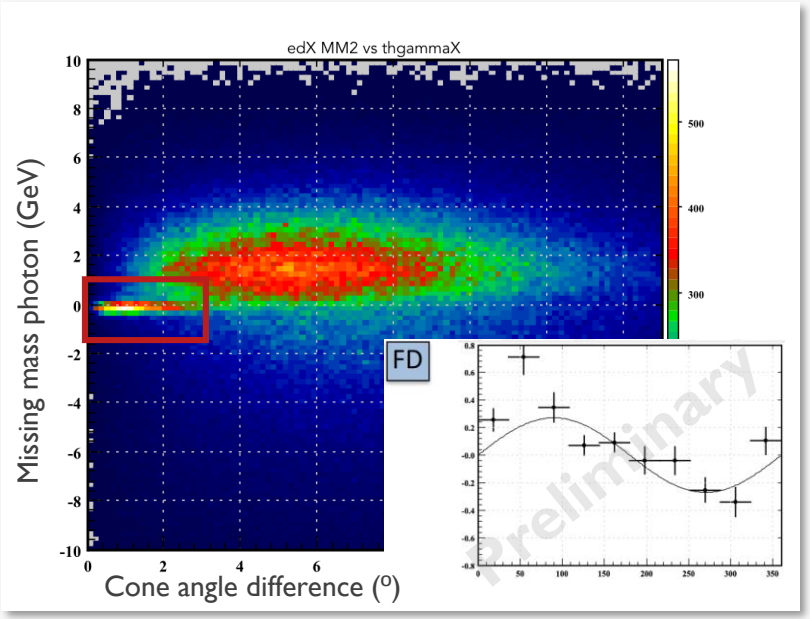
Ongoing analysis

Coherent DVCS on Deuterium

Lead analyzer: A. Bisseli (Fairfield U.)

- Deuterium is a spin-1 particle, with 9 GPDs
- Pioneering measurement, with low statistics

$$A_{LU} \propto Im\left[\frac{2G_1\mathcal{H}_1+(G_1-2\tau G_3)(\mathcal{H}_1-2\tau\mathcal{H}_3)+\frac{2}{3}\tau G_3\mathcal{H}_5}{2G_1^2+(G_1-2\tau G_3)^2}\right]$$



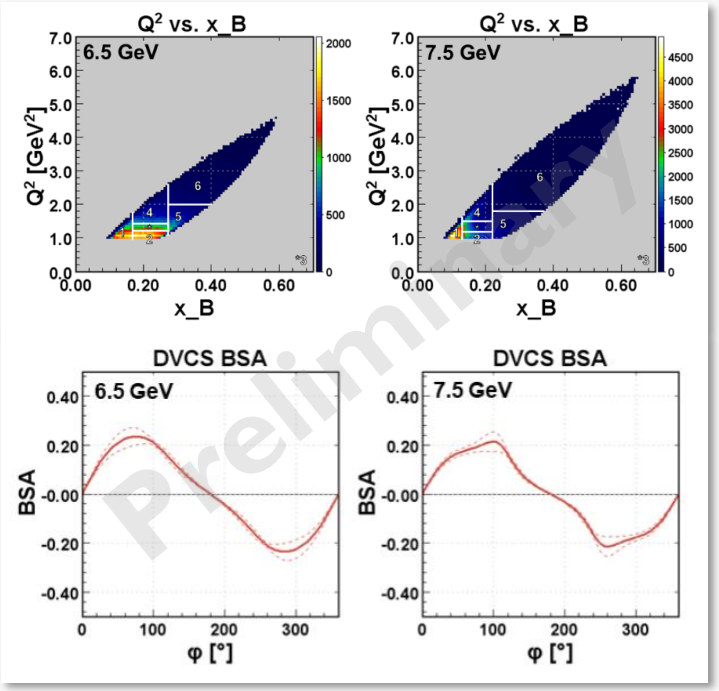
Ongoing analysis

DVCS on the proton at 6.5 and 7.5 GeV

Lead analyzer: J.A. Tan (Kyungpook National U.)

- Similar phase space as CLAS6 with better precision

$$A_{LU} \propto Im\left[F_1\mathcal{H}+\xi(F_1+F_2)\tilde{\mathcal{H}}-\frac{t}{4M^2}F_2\mathcal{E}\right]$$



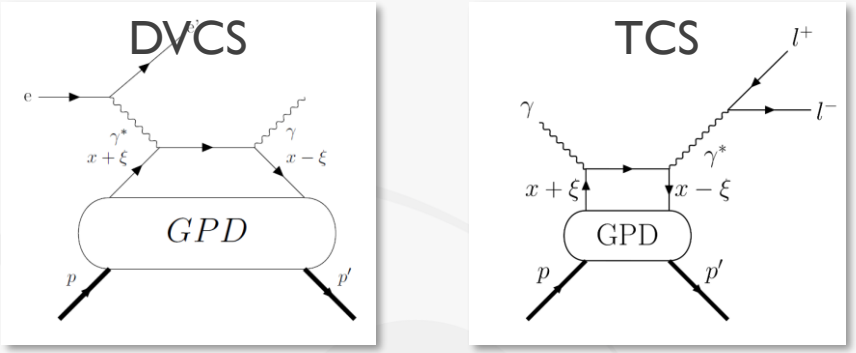
Ongoing analysis

Timelike Compton Scattering on the proton

Lead analyzer: P. Chatagnon (JLab)

The Timelike Compton Scattering reaction

- The TCS reaction is the symmetric from the DVCS one.



- Two main motivations for the measurement:
  - Test of the GPD universality, via the BSA measurement

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto \frac{\frac{L_0}{L}\sin\phi\frac{(1+\cos^2\theta)}{\sin(\theta)}\mathrm{Im}\mathcal{H}}{d\sigma_{BH}}$$

  - Access to Re($\mathcal{H}$), via the forward/backward asymmetry

$$A_{FB}(\theta_0,\phi_0) = \frac{d\sigma(\theta_0,\phi_0) - d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}{d\sigma(\theta_0,\phi_0) + d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}$$

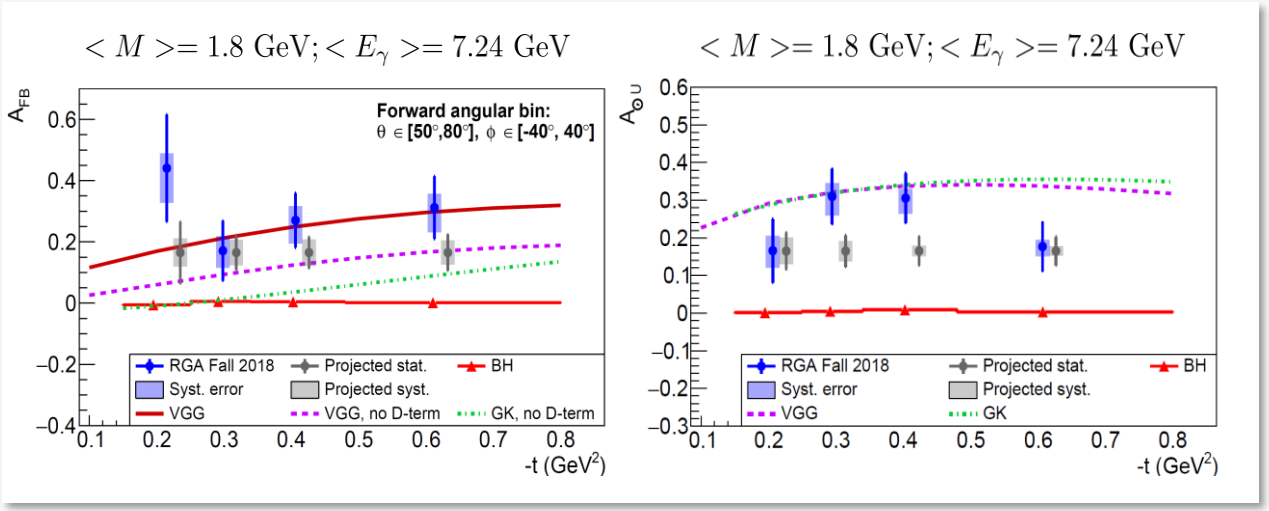
$$\propto \frac{\frac{L_0}{L}\cos\phi_0\frac{(1+\cos^2\theta_0)}{\sin(\theta_0)}\mathrm{Re}\mathcal{H}}{d\sigma_{BH}(\theta_0,\phi_0) + d\sigma_{BH}(180^\circ-\theta_0, 180^\circ+\phi_0)}$$

Analysis strategy

- Use quasi-photoproduction events: $ep \to (e')p'e^+e^-$

Projections for the full proton target dataset (RG-A)

- Only a fraction of RG-A dataset was used for in the PRL article (1/3)
- New significant improvement on the tracking software have been done since 2020 → 50% more efficiency for the 3-particle final state



Results from First Measurement of Timelike Compton Scattering, P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

Published in PRL (2021)

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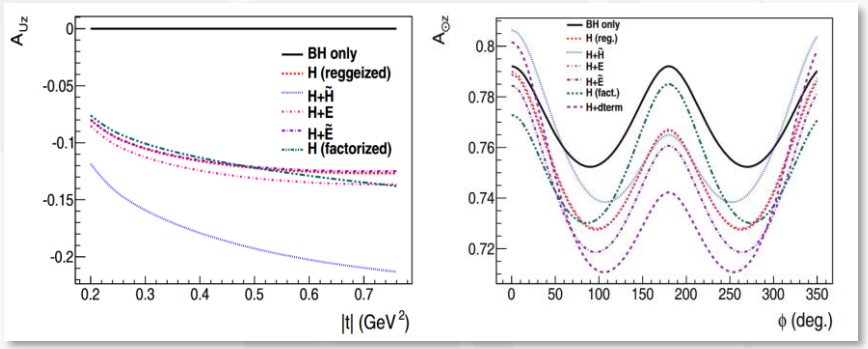
Timelike Compton Scattering on a polarized proton target

Lead analyzer: K. Gates (Glasgow)

Motivations

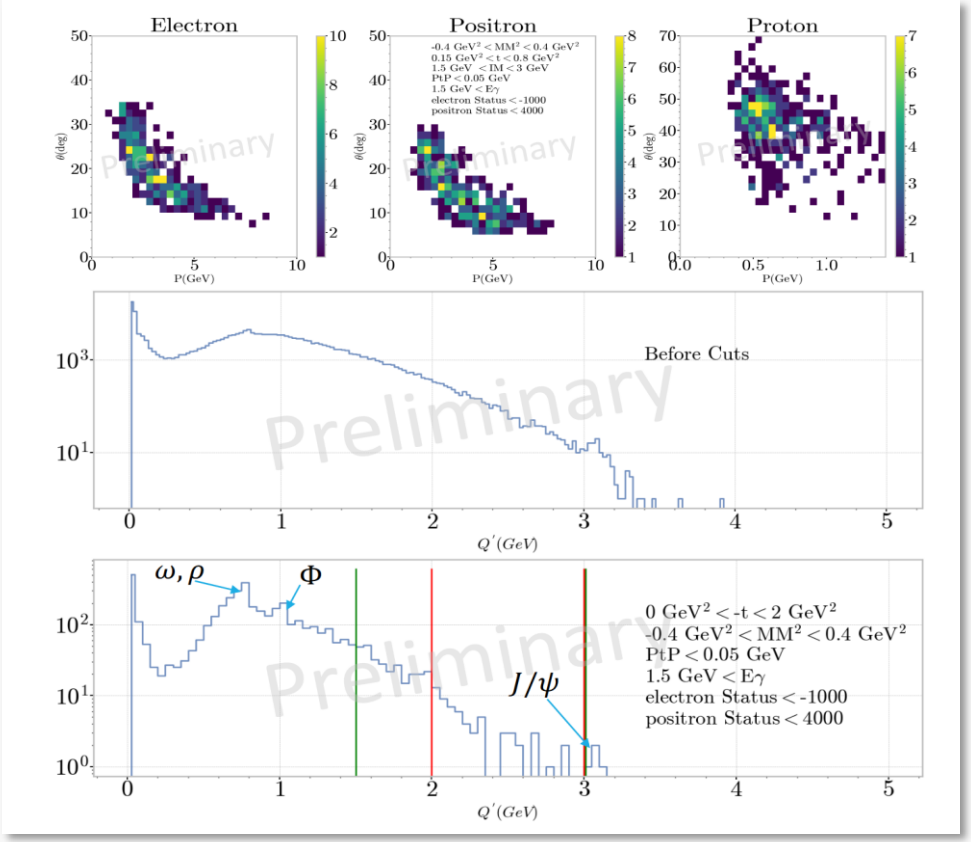
- TCS spin asymmetries provide a complementary way to access CFFs to DVCS
- RG-C data will allow to access 3 spin-polarization observables of TCS
  - BSA: $A_{\odot U} \propto \mathrm{Im}\mathcal{H}$
  - TSA: $A_{UL} \propto \mathrm{Im}\tilde{\mathcal{H}}$
  - DSA: $A_{LL} \propto \mathrm{Re}\tilde{\mathcal{H}}, \mathrm{Re}\mathcal{H}$
- Model predictions show significant asymmetries:



Figures in Boër, M., Guidal, M., Vanderhaeghen, M. Timelike Compton scattering off the proton and generalized parton distributions. Eur. Phys. J. A 51, 103 (2015)

Very preliminary results

- Use quasi-photoproduction event: $ep \rightarrow (e')p'e^+e^-$
- Only ~6% of the total dataset shown



Ongoing analysis

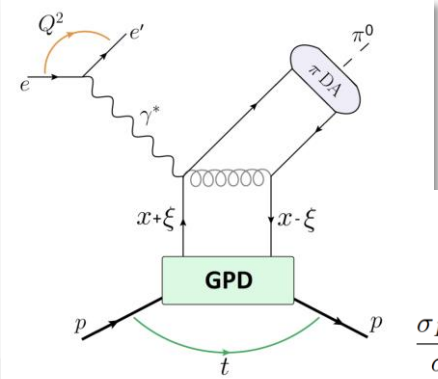
Jefferson Lab

clas

Beam Spin Asymmetry Measurements of Deeply Virtual π^0 Production with CLAS12

Lead analyzer: A. Kim (Connecticut)

Analysis strategy

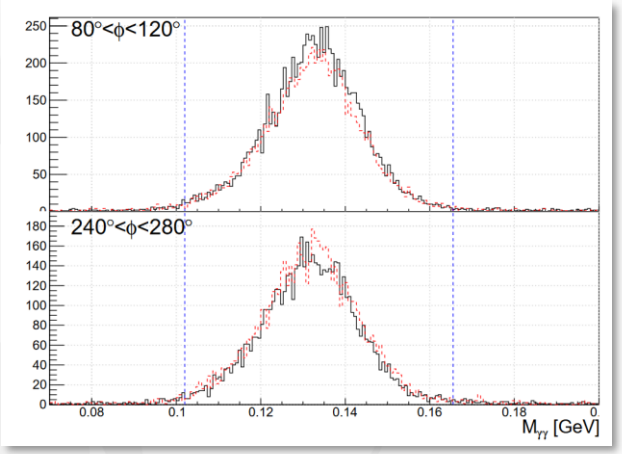


- sin(φ) of the BSA is sensitive to H_T, E_T, $\tilde{H}_T$

$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$

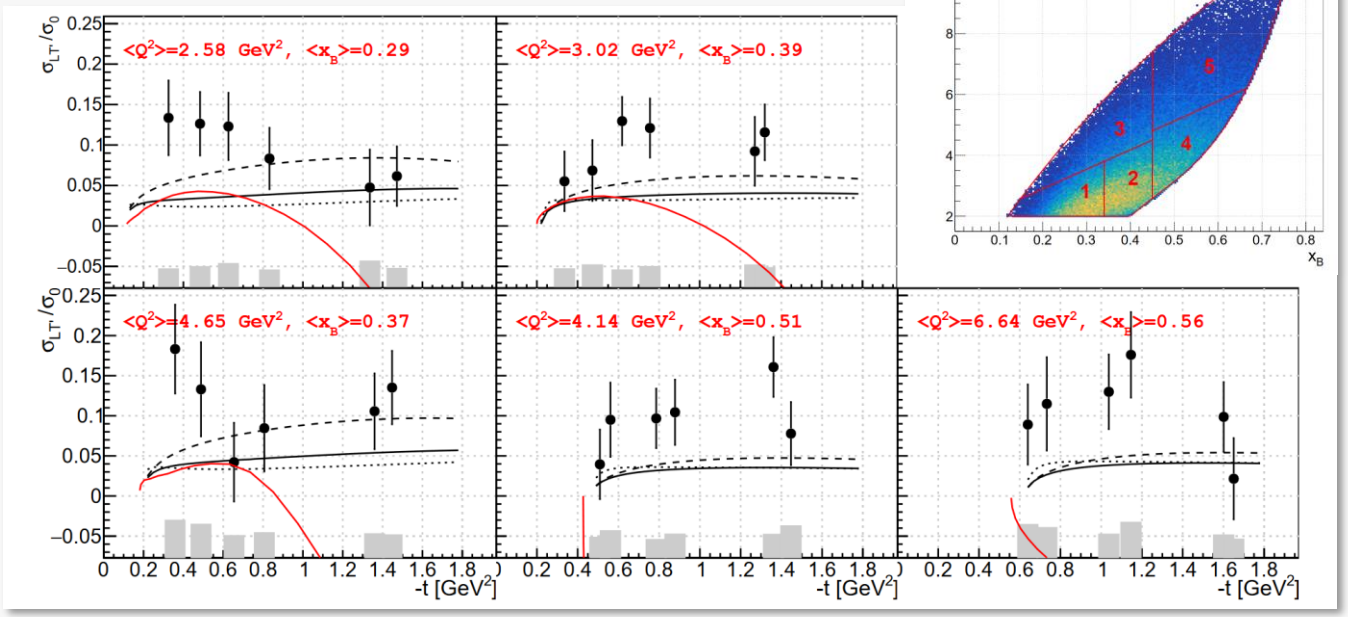
$$\frac{\sigma_{LT'}}{\sigma_0} \sim \frac{Im[\langle\bar{E}_T\rangle^*\langle\widetilde{H}\rangle+\langle H_T\rangle^*\langle\widetilde{E}\rangle]}{(1-\xi^2)\left|\langle H_T\rangle\right|^2-\frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2+\epsilon\sigma_L}$$

- Reaction selected in the full final state topology: $ep \rightarrow e'p'\gamma\gamma$



Results

- Multidimensional extraction of the BSA
- Comparison with model predictions (GK and JML) has been performed
- Models seem to underestimate the data

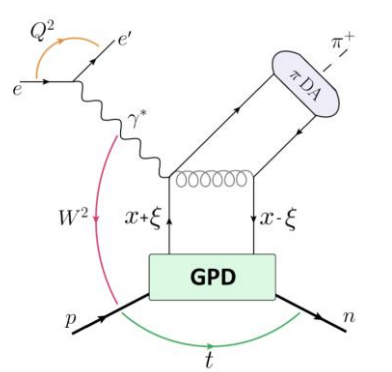


To be submitted to PLB

Hard exclusive π^+ electro-production off protons in the GPD regime

Lead analyzer: S. Diehl (Giessen/Connecticut)

Analysis strategy

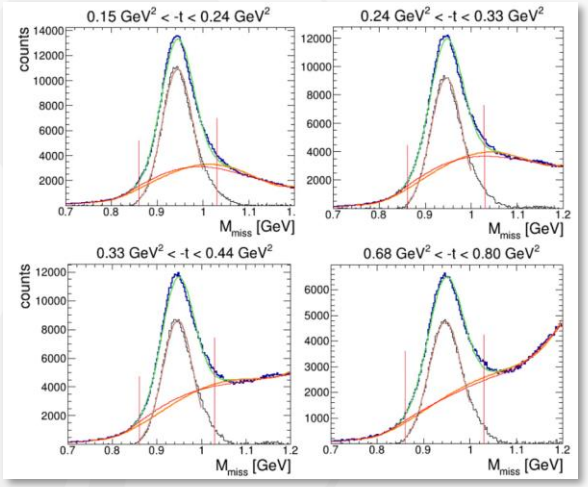


- sin(φ) of the BSA is sensitive to H_T

$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$

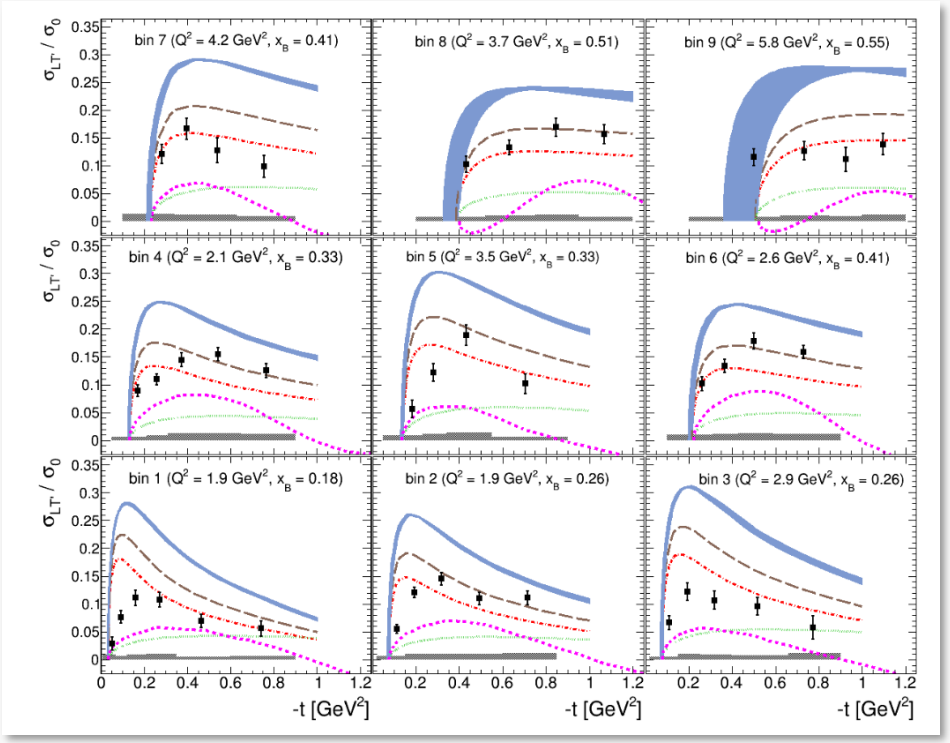
$$\frac{\sigma_{LT'}}{\sigma_0} \sim \frac{Im\left[\langle H_{T-eff}\rangle^* \langle \tilde{E}_{eff}\rangle\right]}{\left|\langle H_{T-eff}\rangle\right|^2+\epsilon\sigma_L}$$

- Avoid resonance region:
  $W > 2$ GeV
- *Reaction extracted in the ep → e π⁺(n) topology*



Published results

- Very first multidimensional measurement of the π^+ electro-production BSA
- Comparison with various model predictions (JML and GK)



Figures in A multidimensional study of the structure function ratio σLT′/σ0 from hard exclusive π+ electro-production off protons in the GPD regime, S. Diehl et al. (CLAS Collaboration), *Phys.Lett.B* 839 (2023) 137761

Published in PLB (2023)

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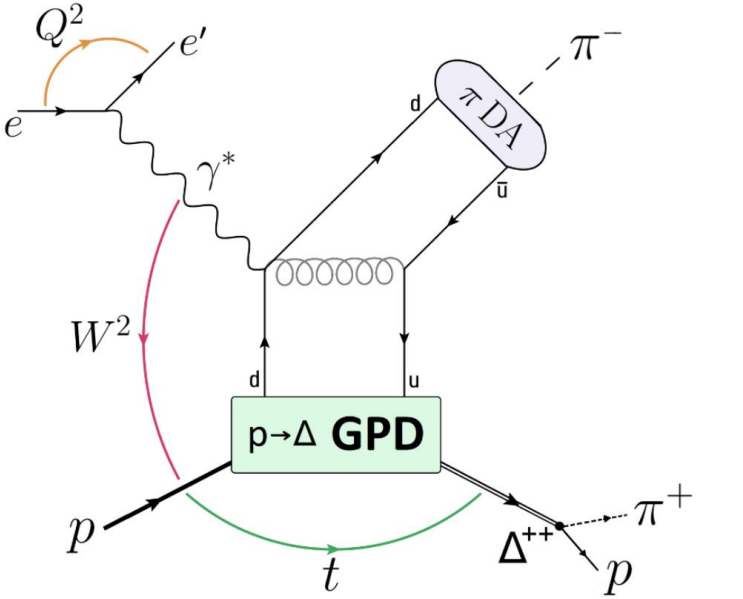
π−Δ++ electroproduction beam-spin asymmetries off the proton

Lead analyzer: S. Diehl (Giessen/Connecticut)

Transition GPDs

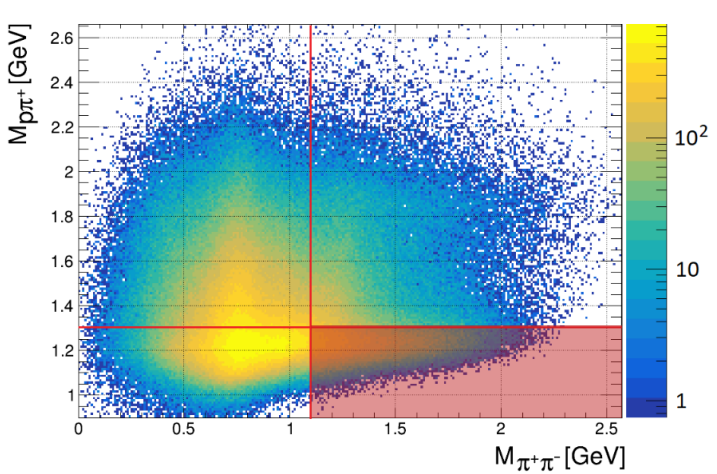
- 16 transition GPDs, generalizing the GPDs to N → Δ processes
- No experimental data

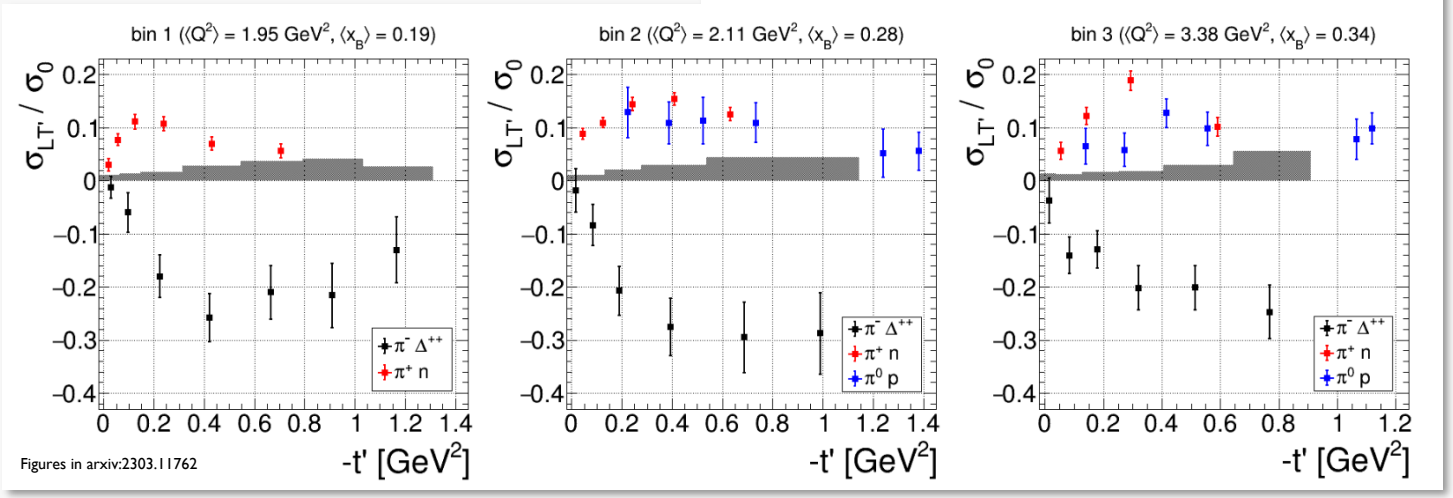


Analysis strategy and results

- $ep \rightarrow e' p\, \pi^-(\pi^+)$ topology
- Avoid resonance region
- BSA fitted with a sin(φ) shape

$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$





Exploratory measurement which needs a strong theoretical support

Accepted in PRL last week

Jefferson Lab

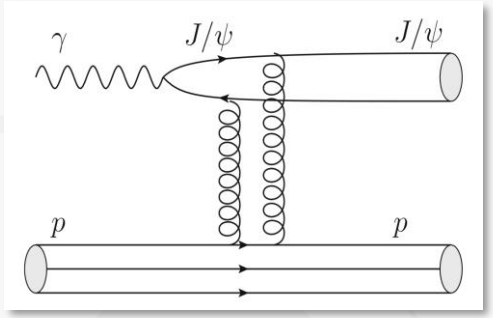
clas

J/ψ photoproduction near threshold on proton and neutron

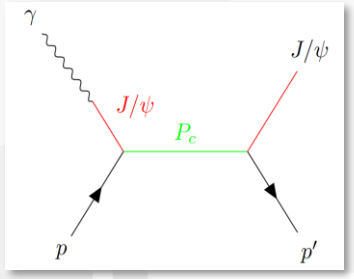
Lead analyzers: P. Chatagnon (JLab) / M. Tenorio Pita (ODU) / R. Tyson (Glasgow)

Motivations

- Probe the gluon content of the proton (under 2-gluon exchange assumption and no open-charm)

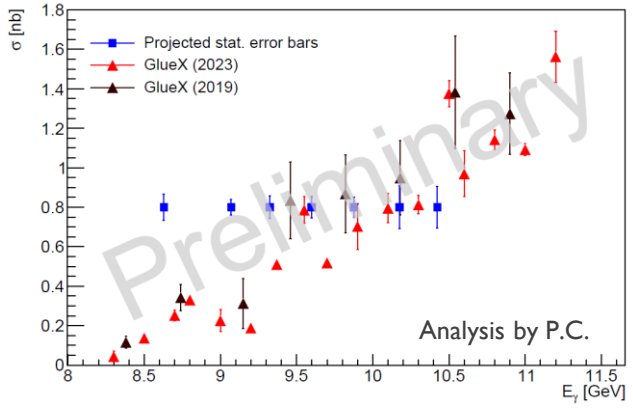


- The t-dependence of the cross-section allow to access gluon Gravitational Form Factors (GFFs), mass radius of the nucleon
- Model-dependent limit on the branching ratio of the Pc pentaquark

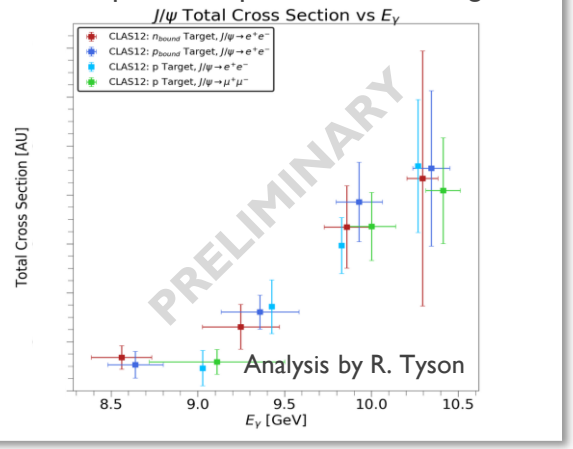


Quasi-photoproduction events ($ep \to (e')p'e^+e^-$ or $ep \to (e')p'\mu^+\mu^-$)

Expected statistical error bars for the full proton dataset

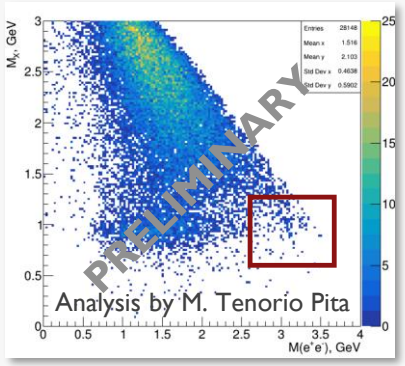


Comparison of proton/neutron target



Tagged-photoproduction ($ep \to e'(p')e^+e^-$)

- Scattered electron detected in the Forward tagger
- Other topologies and muon final state to be tested



Ongoing analysis

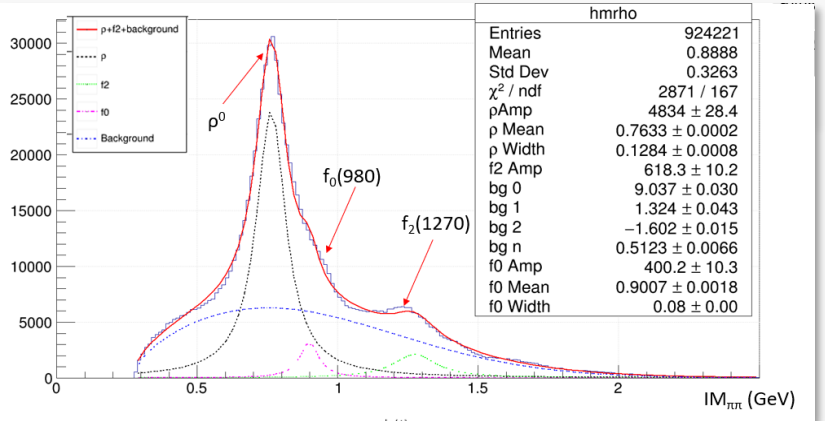
Jefferson Lab

Other DVMP measurements

ρ DVMP on proton

Lead analyzer: N. Trotta (Connecticut)

- Reaction reconstructed in the $ep \rightarrow e'\pi^+\pi^-(p)$ channel
- Preliminary BSA is extracted

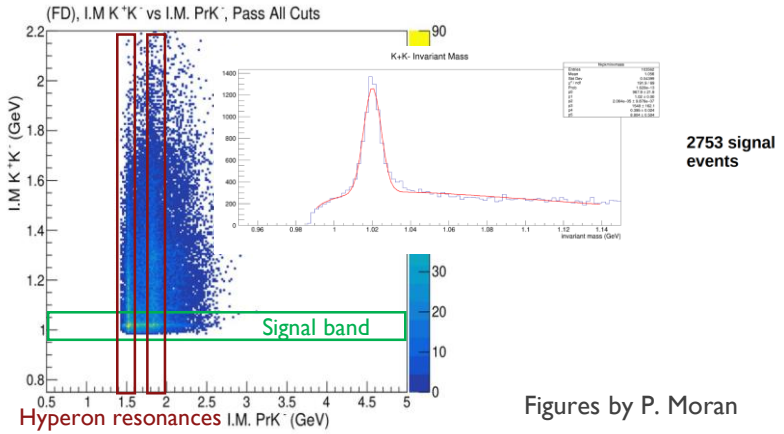


Ongoing analysis

ϕ DVMP

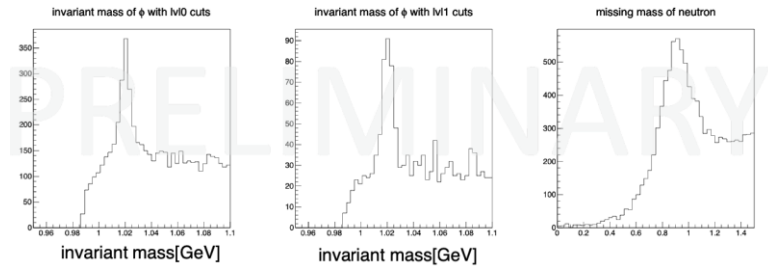
Lead analyzers: P. Moran (MIT) / N. Ram (CEA Saclay)

Cross-section extraction on proton target data



Figures by P. Moran

BSA measurement on neutron



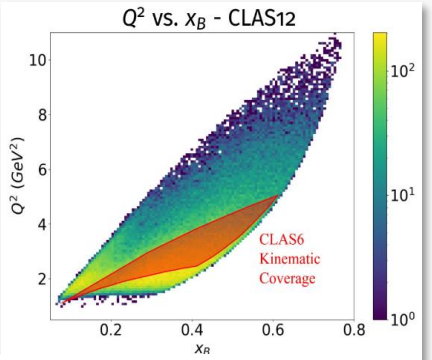
Figures by N. Ram

Ongoing analysis

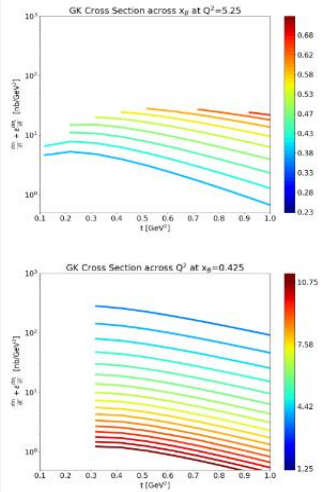
π⁰ DVMP on proton cross section measurement

Lead analyzer: R. Johnston (MIT)

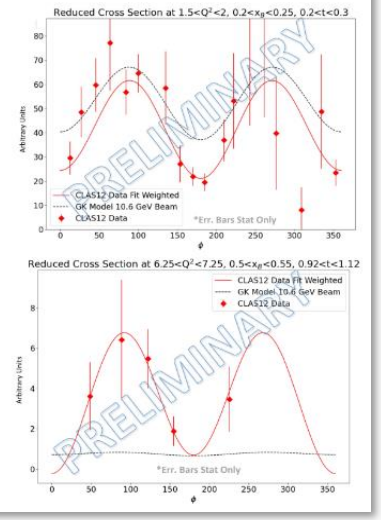
- Significant extension of CLAS6 kinematic reach



Model Predictions



GK and CLAS12 Data

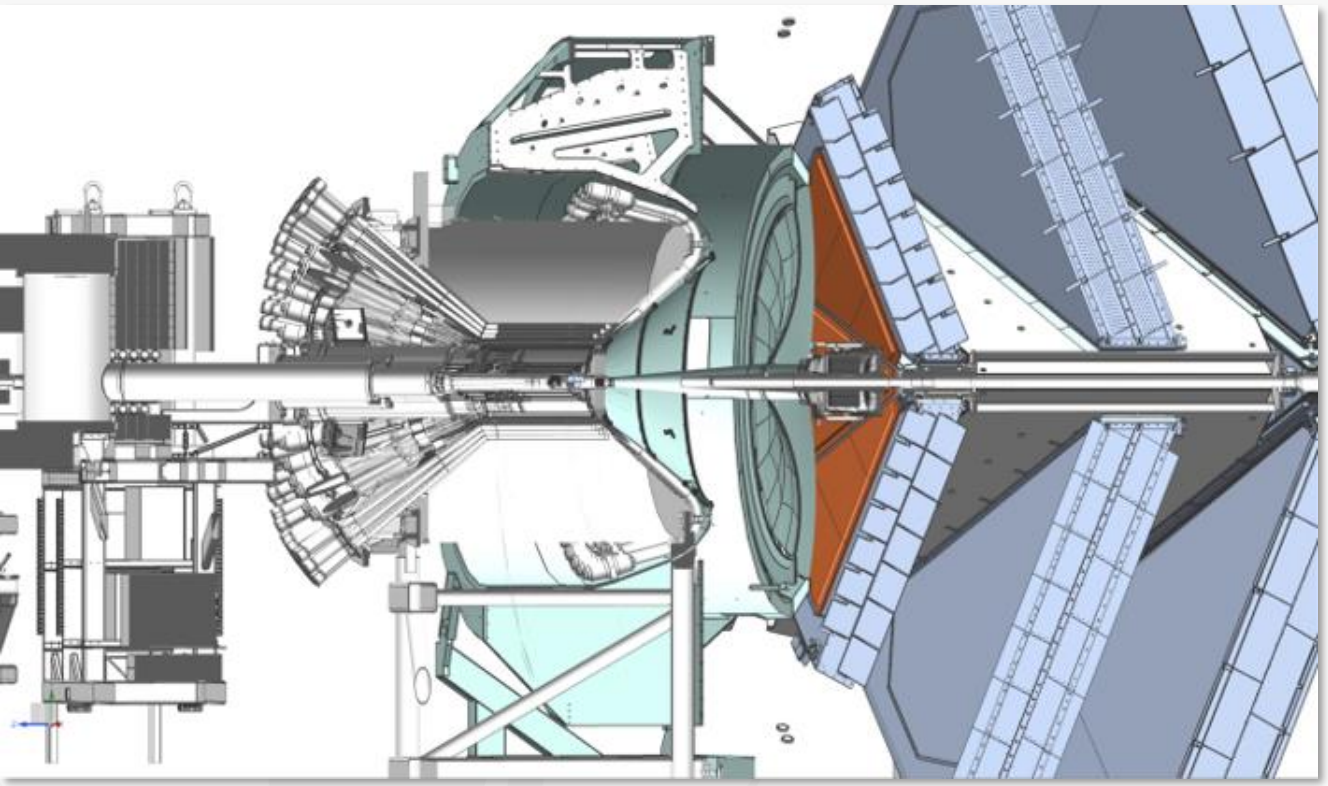


Ongoing analysis

A mid-term perspective with CLAS12: Luminosity upgrade

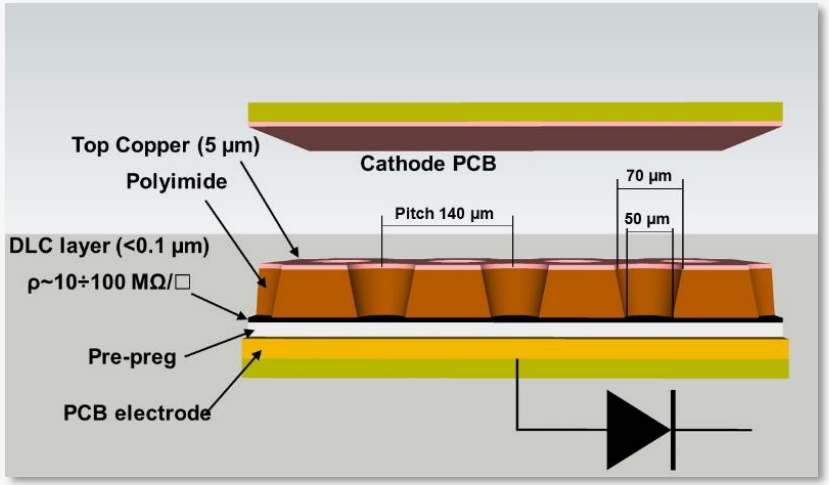
- Exclusive reaction have typically a low cross-section
- Each additional detected track/particle comes with a detection efficiency "penalty"
- These measurement require large luminosity, which is mostly limited by DC occupancies in CLAS12

A potential solution



Figures courtesy of R. Paremuzyan

- μRwell-based detector in front of DC region 1…

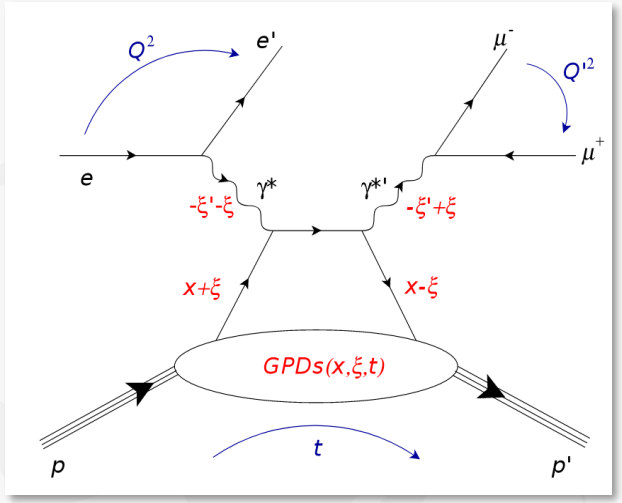


- … combined with increased efficiency of AI tracking, already in place for the current data-processing
- Goal: doubling the luminosity

A long term perspective: Double DVCS measurement

$$ep \to e'\mu^+\mu^- p$$

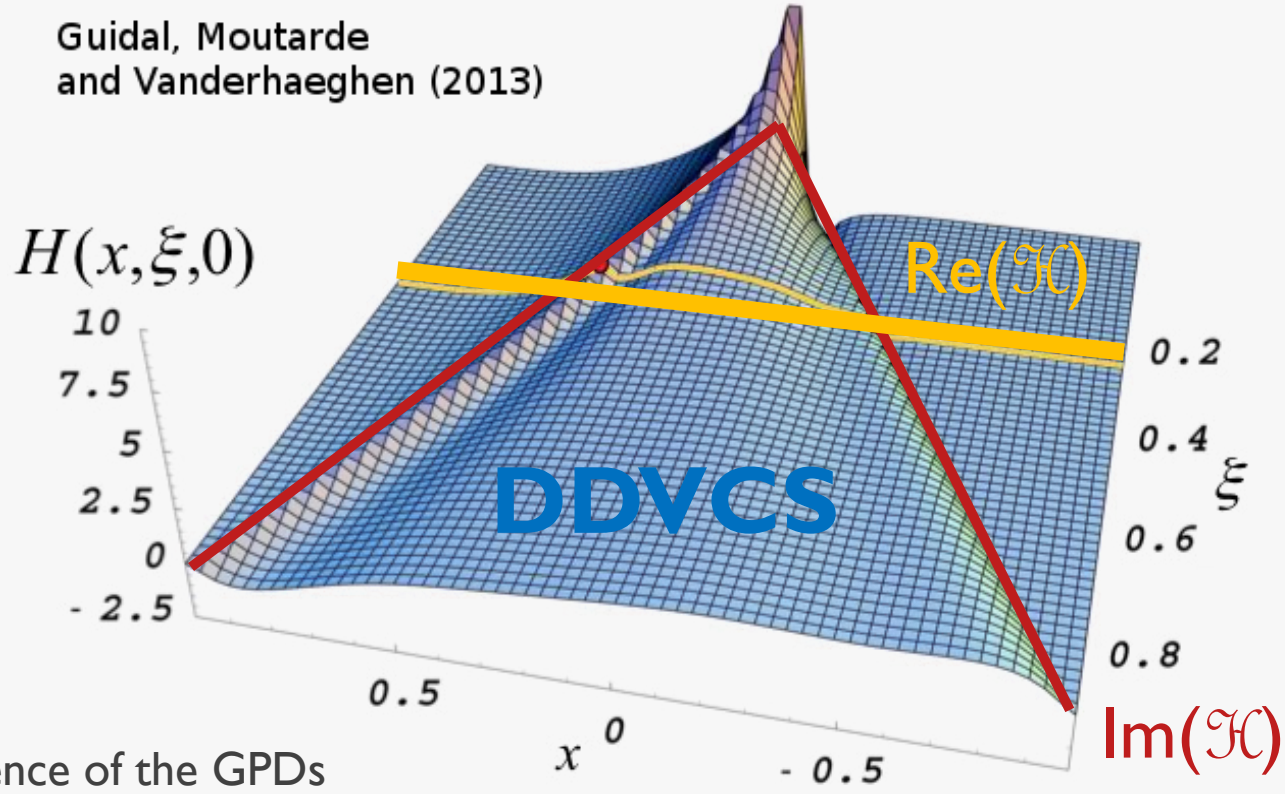
Capturing the complete kinematic dependence of GPDs



$$\mathcal{H}(\xi',\xi,t) = \int_{-1}^{1} dx H(x,\xi,t)\left(\frac{1}{\xi'-x-i\epsilon} - \frac{1}{\xi'+x-i\epsilon}\right)$$

$$Im\mathcal{H}(\xi',\xi,t) \propto H(\xi',\xi,t) - H(-\xi',\xi,t)$$

→ Allow to completely map the kinematic dependence of the GPDs



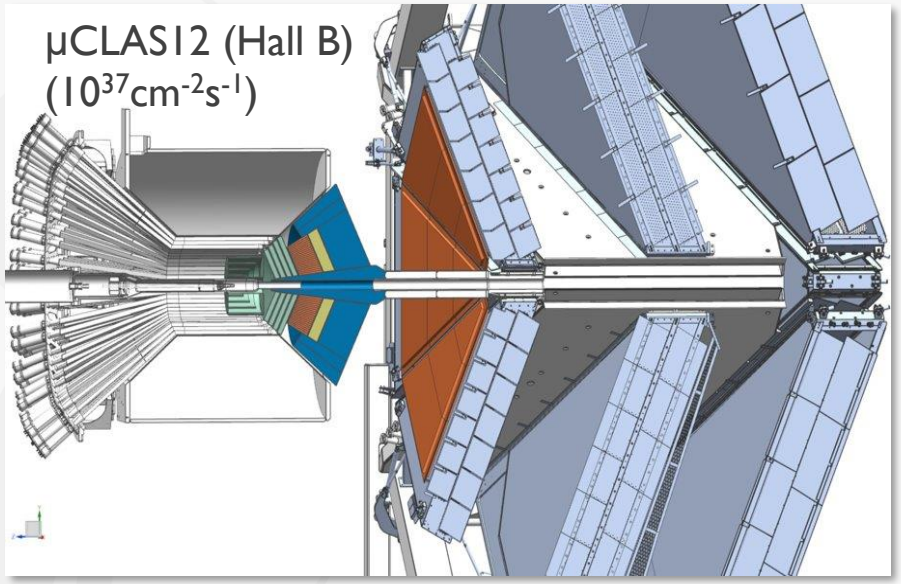
A long term perspective: Double DVCS measurement

$$ep \to e'\mu^+\mu^- p$$

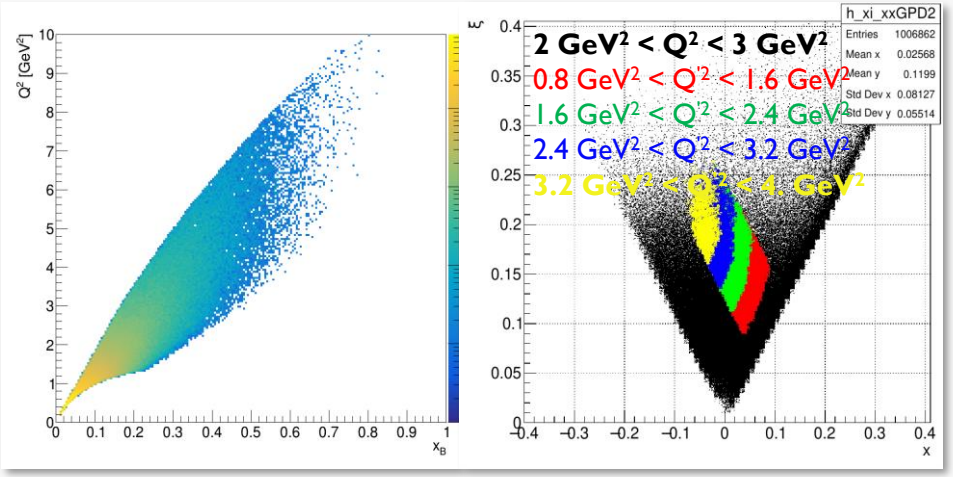
- Two main challenges for DDVCS measurement:
  1. Low x-section: requires high-luminosity
  2. Muon detection needed

A potential solution: μCLAS12

- Luminosity increase by a factor 100
- Shielding to reduce DC occupancy and pion background
- Additional calorimeter for electron ID
- New tracking system around the target



Kinematic reach for DDVCS with μCLAS12



Figures courtesy of Rafayel Paremuzyan

Material from LOI-12-16-004 (Stepanyan, Paremuzyan, Baltzell, De Vita,Ungaro et al.)

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Summary and outlook

- CLAS12 is the ideal detector for exclusive reaction measurement with its large acceptance able to detect multi-particle final state
- Multiple dataset with different beam energies and targets allow to explore a large range of reactions and kinematics

- The exclusive reaction program of CLAS12 is vibrant:
  - ~15 ongoing analysis
  - Already some impactful results have been published (DVCS, TCS, Transition GPDs)
  - Some results are well advanced, stay tuned for more results !

- Many very exciting plans to extend this program in the future: HL-CLAS12, μCLAS12, and positron beam (see E. Voutier's presentation on Wednesday)